LCA Case Studies

Ethanol Fuels: E10 or E85 – Life Cycle Perspectives

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DOI: http://dx.doi.org/10.1065/lca2005.02.201

Abstract

Goal and Scope. The environmental performance of two ethanol fuel applications (E10 and E85) is compared (E10 fuel: a mixture of 10% ethanol and 90% gasoline by volume, and E85 fuel: a mixture of 85% ethanol and 15% gasoline by volume).

Methods. Two types of functional units are considered here: An ethanol production-oriented perspective and a traveling distance-oriented perspective. The ethanol production-oriented functional unit perspective reflects the fact that the ethanol fuel supply (arable land or quantity of biomass used in ethanol fuel) is constrained, while the traveling distance-oriented functional unit implies that the ethanol fuel supply is unlimited.

Results and Discussion. In the ethanol production-oriented functional unit perspective, the E10 fuel application offers better environmental performance than the E85 fuel application in terms of natural resources used, nonrenewable energy and global warming. However, in the calculations based on the traveling distance perspective, the E85 fuel application provides less environmental impacts in crude oil consumption, nonrenewable energy and global warming than the E10 fuel application.

Conclusions and Outlook. The choice of functional units significantly affects the final results. Thus the functional unit in a descriptive LCA should reflect as nearly as possible the actual situation associated with a product system. Considering the current situation of constrained ethanol fuel supply, the E10 fuel application offers better environmental performance in natural resources used, nonrenewable energy and global warming unless the fuel economy of an E85 fueled vehicle is close to that of an E10 fueled vehicle.

Keywords: Biofuel; E10; E85; ethanol fuels; functional unit

Introduction

Ethanol derived from biomass is regarded as a substitute transportation fuel for gasoline. About 12 Mm^3 of ethanol are produced annually, primarily from corn grain, in the United States [1]. Ethanol is used as liquid fuel in two ways: E10 (a mixture of 10% ethanol and 90% gasoline by volume) and E85 (a mixture of 85% ethanol and 15% gasoline by volume). Currently E10 fuel is for more widely used than E85 fuel. Ethanol used in E10 fuel accounts for approximately 99% of the total ethanol consumed as transportation fuel, and the volume of E10 fuel used is about 21% of the total volume of gasoline consumed in the transportation sector in the United States [2]. The consumption of ethanol as liquid fuel has rapidly increased in recent years as seen in **Fig. 1**. The increase of the ethanol consumption rate is much higher than the increase in gasoline consumption rate. Ethanol consumption in both E10 and E85 fuels since 1999 has increased more rapidly than in previous years, while the rate of increase of gasoline consumption is almost steady. Particularly the E85 fuel use experienced a great leap between 1999 and 2000.

Several studies have scrutinized the environmental performance of corn-based ethanol, especially nonrenewable energy consumption and greenhouse gas emissions [3–9]. Most studies have concluded that corn-based ethanol used as liquid fuel could displace gasoline used in transportation sector and reduce global warming. A recent study by Kim and Dale [10] carried out a life cycle assessment (LCA) study on ethanol application as an E10 fuel, concluding that the utilization of ethanol as liquid fuel would have environmental credits in terms of nonrenewable energy consumption and global warming. However, Kim and Dale [10] indicated that ethanol used as liquid fuel might also have adverse impacts on acidification and eutrophication due to emissions related to nitrogen (and phosphorus) in the agricultural process. They

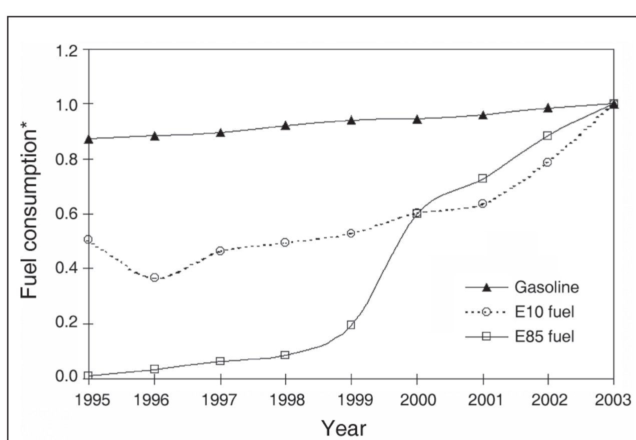

Fig. 1: Temporal trend of vehicle fuel consumption in the United States [2] [*: fuel consumption in 2003 is the baseline (=1) for each type of fuel]

found that an integrated biorefinery, in which ethanol is produced from both corn stover and corn grain, would have the potential for a better environmental impact profile when utilizing ethanol as liquid fuel compared to a system based on corn grain only.

This study carries out an LCA study on ethanol applications for E10 and E85 fuels to compare the environmental profiles of these two applications. The environmental profile is addressed in terms of natural resources used (e.g., crude oil, coal, and natural gas), nonrenewable energy consumption, global warming, acidification and eutrophication.

The goal of this study is to compare the environmental impacts of ethanol applications (i.e., E10 and E85), resulting from two types of functional units. The environmental impacts addressed here reflect the differences between ethanol fueled and gasoline fueled vehicle operations.

1 Methods

In this study, the function is defined as driving a passenger vehicle. Two types of functional units are applied in this study: ethanol production-oriented (arable land or quantity of biomass used in ethanol fuel) and traveling distance-oriented. An ethanol production-oriented functional unit is defined as one kg of ethanol, indicating that the capacity of bioethanol production is a constraint factor, namely, the supply of bioethanol is limited. This functional unit also implies that the availability of agricultural land (or biomass) for ethanol production is constrained. A traveling distance-oriented functional unit is application-oriented and defined as one km driven by an ethanol fueled vehicle. This functional unit implies that the supply of bioethanol is unlimited. Thus arable land (or biomass) for producing ethanol is unconstrained in this functional unit.

The system boundary includes corn cultivation, transportation of grain to a corn wet milling plant, the wet milling process, transportation and distribution of ethanol, and ethanol fueled vehicle operation. A conventional vehicle operation (a gasoline fueled vehicle) is also included in the system boundary to estimate differences in the environmental impacts between ethanol fueled and gasoline fueled vehicle operations. The avoided product systems for coproducts in wet milling (e.g., corn gluten meal (CGM), corn gluten feed (CGF) and corn oil) are also included in the system boundary to allocate the environmental burdens to ethanol. Therefore, the allocations are done by introducing alternative product systems – the system expansion approach. Ethanol fueled and gasoline fueled vehicle operations are sufficient to compare the environmental performance of ethanol fuel application systems. However, the system boundary includes the full life cycle of the ethanol application system because one of the goals in this study is to address the environmental aspects of ethanol use. The environmental burdens associated with the vehicle production system and vehicle maintenance are not included in the analysis.

Important factors in this study are the fuel economy of vehicle and the air emissions associated with operating the vehicle. A compact passenger car is used as a reference vehicle, for which the fuel economy is available from the United States Department of Energy [11]. The combined fuel economy of an E10 fueled vehicle, which is based on 55% city driving and 45% highway driving, is equal to that of a conventional vehicle (gasoline fueled), 10.1 km L^{-1}. The combined fuel economy of an E85 fueled vehicle is 7.5 km L^{-1}. Note that the volume in the fuel economy estimate is expressed as gasoline equivalent volume. Air emissions from driving vehicles are also available in the US EPA [12]. Carbon dioxide emissions are estimated by the amount of gasoline. SO_x emissions are calculated from sulfur content in gasoline [6]. **Table 1** summarizes air emissions from driving using each fuel.

The corn farm is assumed to be located in Scott County, Iowa, which has ethanol plants in adjacent counties. The inventory information on each process is available elsewhere [10]. The potential impact categories considered here are natural resources used, nonrenewable energy, global warming, acidification, and eutrophication. Carbon contents in biobased products are not taken into account in greenhouse gases because carbon in biobased products would be released to the atmosphere in the downstream portions of the system. The environmental impacts on natural resources used and nonrenewable energy are presented without further characterization. Global warming is estimated by the 100-year global warming potential. The characterization factors for regional impacts are adopted from the TRACI model (Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts) developed by the United States Environmental Protection Agency [13].

Table 1: Air emissions from driving a compact passenger vehicle after 80,000 km used [6,12]

Air emissions	Unit	Gasoline fueled	E10 fueled	E85 fueled
CO_2[a]	g km^{-1}	229.6	214.0	65.4
CO	mg km^{-1}	468.9	227.8	248.5
HCHO	mg km^{-1}	0.70	0.62	0.62
Non-methane organic gases	mg km^{-1}	27.3	27.3	27.3
NO_x	mg km^{-1}	62.1	93.2	124.3
SO_x[b]	mg km^{-1}	48.8	45.5	13.9

[a] Carbon dioxide emission in driving a gasoline fueled vehicle is obtained from the GREET model [6]

[b] Sulfur content in gasoline is obtained from the GREET model [6]

2 Results and Discussion

Ethanol production-oriented functional unit perspective. In the ethanol production-oriented functional unit perspective, one kg of ethanol is able to propel an E10 fueled compact passenger vehicle 123 km and an E85 fueled compact passenger vehicle 7.9 km. The environmental burdens associated with equivalent distances driven by a gasoline fueled vehicle are subtracted from those of the ethanol production system. One kg of ethanol could save 1.02 kg of crude oil in the E10 fuel application and 0.8 kg of crude oil in the E85 fuel application. Ethanol fuel could also conserve nonrenewable energy by 31 MJ kg^{-1} in the E10 fuel application and by 19 MJ kg^{-1} in the E85 fuel application. Greenhouse gas emissions could be reduced by utilization of ethanol derived from corn grain as liquid fuel. Therefore, using ethanol as a liquid fuel for vehicles results in environmental credits for crude oil consumption, nonrenewable energy and global warming. However, the application of ethanol in liquid fuels has adverse effects on acidification and eutrophication regardless of its fraction (E10 or E85) in that liquid fuel. The adverse effects are mainly because of environmental burdens released during corn cultivation, particularly nitrogen and phosphorus related emissions from the soil. The potential environmental impacts based on the ethanol production-oriented functional unit perspective are summarized in **Table 2**.

Results show that the environmental performance of the E10 fuel application is slightly better in natural resources used, nonrenewable energy and global warming than that of the E85 fuel application because an E10 fueled vehicle travels farther than an E85 fueled vehicle. Although NO_x emissions from the tailpipe in an E10 fueled vehicle are lower than that in an E85-fueled vehicle, acidification and eutrophication in the E10 fuel application are slightly higher than in the E85 fuel application. This is because 1) ethanol-fueled vehicles (E10 and E85) release more NO_x emissions than a gasoline-fueled vehicle, and 2) the fuel economy of an E10 fueled vehicle is much higher than that of an E85 fueled vehicle.

Traveling distance-oriented functional unit perspective. One kilometer driven requires 8 g of ethanol in the E10 fuel application and 127 g of ethanol in the E85 fuel application. Use of ethanol as liquid fuel could save crude oil at the rate of 8 g km^{-1} in the E10 fuel application and by 102 g km^{-1} in the E85 fuel application. One kilometer driven by an E10 fueled vehicle and by an E85 fueled vehicle could reduce greenhouse gas emissions by 15.3 g CO_2 equivalent and by 139 g CO_2 equivalent, respectively. **Table 3** summarizes the potential environmental impacts estimated based on the traveling distance-oriented functional unit perspective. In this functional unit, the E85 fuel application offers better environmental performance than the E10 fuel application in terms of crude oil used, nonrenewable energy, and global warming because the environmental burdens are normalized to the distance traveled by a vehicle and the supply of ethanol is not constrained. However, the E10 fueled application offers better environmental performance in acidification and eutrophication than the E85 fueled application.

Comparison. In the ethanol production-oriented functional unit perspective, the E10 fuel application offers better environmental performance than the E85 fuel application in terms of crude oil consumption, nonrenewable energy and global warming. However, in the calculations based on the traveling distance perspective the E85 fuel application provides less environmental impacts in crude oil consumption, nonrenewable energy and global warming than the E10 fuel application. In the ethanol production-oriented functional unit

Table 2: Potential environmental impacts estimated based on ethanol production-oriented functional unit perspective

	Unit	E10 fuel	E85 fuel
Coal	g kg^{-1}	486	496
Crude oil	g kg^{-1}	–1,016	–800
Natural gas	g kg^{-1}	27.2	65.0
Nonrenewable energy	MJ kg^{-1}	–30.7	–19.1
Global warming	g CO_2 eq. kg^{-1}	–1.88	–1.10
Acidification	moles H^+ eq. kg^{-1}	1.37	1.29
Eutrophication	g N eq. kg^{-1}	1.14	1.13

Table 3: Potential environmental impacts estimated based on traveling distance-oriented functional unit perspective

	Unit	E10 fuel	E85 fuel
Coal	g km^{-1}	4.0	62.9
Crude oil	g km^{-1}	–8.3	–101.5
Natural gas	g km^{-1}	0.22	8.24
Nonrenewable energy	MJ km^{-1}	–0.2	–2.4
Global warming	g CO_2 eq. km^{-1}	–15.3	–139.4
Acidification	moles H^+ eq. km^{-1}	0.01	0.16
Eutrophication	mg N eq. km^{-1}	0.01	0.14

perspective, the E85 fuel application has better environmental profiles in acidification and eutrophication than the E10 fuel application, and vice versa in the traveling distance-oriented functional unit perspective.

Results from the two types of functional units considered are totally different from each other in most of the environmental impact categories except for coal and natural gas consumption. Thus the choice of functional unit to normalize the environmental impacts significantly affects the final conclusions.

Sensitivity analysis. Sensitivity analyses have been carried out on 1) vehicle type, and 2) fuel economy of an E85 fueled vehicle. Tailpipe emissions from a sport utility vehicle (SUV) are also available [12]. The combined fuel economy of an E10 fueled SUV is assumed to be equal to that of a conventional SUV, which is 6.5 km L^{-1}. The combined fuel economy of an E85 fueled SUV is 4.7 km L^{-1}. The combined fuel economy of a SUV is much less than that of a compact passenger vehicle. The tailpipe emissions from a sport utility vehicle are summarized in **Table 4**.

Results from the sensitivity analysis show that the E10 application in the ethanol production-oriented functional unit perspective has better environmental performance in all the impact categories considered here than the E85 application because there is no difference in NO_x emissions from vehicles, which is one of the primary environmental burdens in acidification and eutrophication during the vehicle operations. In the traveling distance-oriented functional unit perspective, similar conclusions for a compact passenger vehicle are observed. It is of interest that the fuel-specific environmental impacts (i.e., crude oil used, nonrenewable energy and global warming) associated with the E10 fuel application in the ethanol production-oriented functional unit perspective remain constant regardless of the vehicle types because the ratio of ethanol in the E10 fuel is fixed. In the traveling distance-oriented functional unit perspective, the fuel-specific impacts associated with a SUV operated by both the E10 and the E85 fuels are better than those of a compact passenger vehicle because there are more environmental credits with respect to the fuel-specific impacts in driving 1 km by a SUV due to a lower fuel economy of a SUV.

The fuel economy is a key factor in this study. Wang [6] assumed that the fuel economy in an E85 fueled vehicle in a near term technology (almost available in the marketplace) is 5% higher than the fuel economy of a gasoline fueled vehicle. The current fuel economy of the E85 fueled vehicle (a compact passenger car) used here is lower than the gasoline fueled vehicle's fuel economy by approximately 26%.

It is expected that increasing fuel economy will offer better environmental performance for the vehicle. The sensitivity analysis investigates how a higher fuel economy for an E85 fueled vehicle affects the comparison of the environmental performances of an E10 and an E85 fueled vehicle. Effects of one percentage point increase in the fuel economy of an E85 fueled vehicle on the environmental impacts associated with the E85 application are summarized in **Table 5**. One percentage point increase in the fuel economy of an E85 fueled vehicle can reduce crude oil consumption by 6.3 g kg^{-1} in the ethanol-oriented functional unit perspective, but increase crude oil consumption by 0.15 g km^{-1} in the traveling distance-oriented functional unit perspective. Ethanol production has a crude oil credit due to avoided crude oil associated with its coproducts (CGM, CGF, corn oil, etc.). A higher fuel economy requires less ethanol for a given traveling distance. These factors imply that a higher fuel economy results in more crude oil consumption in the traveling distance-oriented functional unit.

Table 4: Air emissions from driving a sport utility vehicle after 80,000 km used [6,12]

Air emissions	Unit	Gasoline fueled	E10 fueled	E85 fueled
CO_2 [a]	g km^{-1}	357	333	103
CO	mg km^{-1}	870	932	1,056
Non-methane organic gases	mg km^{-1}	48	50	83
NO_x	mg km^{-1}	62	62	62
SO_x [b]	mg km^{-1}	76	71	22

[a] Carbon dioxide emission in driving a gasoline fueled vehicle is obtained from the GREET model [6]
[b] Sulfur content in gasoline is obtained from the GREET model [6]

Table 5: Reduction rate in the environmental impacts when the fuel economy of an E85 fueled vehicle is increased by one percentage point

	Unit	Reduction rate	
		Ethanol production-oriented functional unit perspective	Traveling distance-oriented functional unit perspective
Coal	g kg^{-1}	0.29	0.46
Crude oil	g kg^{-1}	6.33	–0.15
Natural gas	g kg^{-1}	1.11	0.15
Nonrenewable energy	MJ kg^{-1}	0.34	0.01
Global warming	g CO_2 eq. kg^{-1}	22.82	1.00
Acidification	1000 moles H^+ eq. kg^{-1}	1.90	1.29
Eutrophication	mg N eq. kg^{-1}	4.15	1.34

At the current fuel economy, the E10 fuel application provides better environmental performance than the E85 fuel application in the ethanol production-oriented functional unit perspective in terms of natural resources used (i.e., coal, crude oil, natural gas), nonrenewable energy and global warming. If the fuel economy of an E85 fueled vehicle is equal to that of an E10 fueled vehicle – approximately a 35% increase in the current fuel economy for an E85 fueled vehicle, an E85 fueled vehicle provides better environmental performance in all the impacts considered here than that of an E10 fueled vehicle in the ethanol production-oriented functional unit perspective. However, in the traveling distance-oriented functional unit perspective, an E85 fueled vehicle is unlikely to offer better environmental performance than an E10 fueled vehicle even though the fuel economy of an E85 fueled vehicle is more than double the fuel economy of an E10 fueled vehicle.

3 Conclusions and Outlook

Results from two types of functional units are totally different from each other in most of the environmental impact categories except for coal and natural gas consumption. Thus the choice of the functional unit of a system is important. The functional unit in a descriptive LCA should reflect a situation associated with the current product system. The ethanol production-oriented functional unit perspective reflects the fact that the ethanol production in the United States is constrained due to the availability of biomass (or arable land). The United States Department of Energy projected that the total annual volume of gasoline consumed in the transportation sector in the United States in 2004 is approximately 516 Mm^3, and the volume of gasoline consumed as a pure gasoline fuel is about 79% of the total gasoline volume used in all vehicles [2]. If ethanol fuel replaces the entire pure gasoline fuel used in all vehicles, the E10 fuel application will annually require about 54 Mm^3 of ethanol, and the E85 fuel application will require about 854 Mm^3. The current annual ethanol volume in the United States is 12 Mm^3 [1], indicating that the current capacity of ethanol production is not sufficient to replace the entire pure gasoline fuel in either E10 or E85 fuel forms. Thus the ethanol fuel supply is constrained, and the ethanol-oriented functional unit perspective is more relevant to the current situation. In the future cellulosic ethanol (e.g., ethanol from crop residues, legumes, grass, waste paper, etc.) is expected to be available in the market. If cellulosic ethanol and starch based ethanol could replace the entire pure gasoline fuel, the ethanol fuel supply would not be constrained. In this case the traveling distance-oriented functional unit perspective is more relevant to compare the environmental performance of the ethanol fuel applications. Considering the current situation, the E10 fuel application offers better environmental performance in natural resources used, nonrenewable energy and global warming unless the fuel economy of an E85 fueled vehicle is close to that of an E10 fueled vehicle.

Both the E10 and the E85 fuel applications could save crude oil, conserve nonrenewable energy, and reduce greenhouse gas emissions regardless of the choice of the functional units. However, using ethanol derived from corn grain as liquid fuel increases coal and natural gas consumption, acidification, and eutrophication.

According to the US EPA tailpipe emission data since 2000 [12], there is no consistency with respect to the tailpipe emissions in different vehicles. For example some E85 fueled vehicles release less tailpipe emissions than their gasoline fueled counterpart vehicles, and vice versa in others. Therefore, results from this study are relevant to only specific models of vehicle. There might be large uncertainties in tailpipe emissions, particularly NO_x, non-methane organic gases, and formaldehyde. However, carbon dioxide and sulfur oxide emissions from the tailpipe of vehicles, which depend more on the properties of gasoline, are relatively less uncertain.

Acknowledgements. The authors gratefully acknowledge support provided by Cargill Dow, LLC (Minnetonka, Minnesota, USA), by DuPont Biobased Materials, Inc. (Wilmington, Delaware, USA) and by the Center for Plant Products and Technologies at Michigan State University (East Lansing, Michigan, USA).

References

[1] Renewable Fuels Association (2004): Renewable Fuels Association <http://www.ethanolrfa.org/index.shtml>
[2] Energy Information Administration (EIA) (2004): Alternatives to Traditional Transportation Fuels 2000. United States Department of Energy <http://www.eia.doe.gov/cneaf/alternate/page/datatables/table10.html>
[3] Shapouri H, Duffield JA, Graboski MS (1995): Estimating the net energy balance of corn ethanol. Agricultural Economic Report 721, US Department of Agriculture. Washington DC, USA
[4] Shapouri H, Duffield JA, Wang M (2002): The energy balance of corn ethanol: An update. Agricultural Economic Report 813, US Department of Agriculture. Washington DC, USA
[5] Wang M, Saricks C, Santini D (1999): Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions. ANL/ESD-38, Argonne National Laboratory. Illinois, USA
[6] Wang M (2000): Greet 1.5a – Transportation fuel-cycle model. Argonne National Laboratory, Illinois, USA
[7] Kim S, Dale BE (2002): Allocation procedure in ethanol production system from corn grain: I. System expansion. Int J LCA 7 (4) 237–243
[8] Pimentel D (1991): Ethanol fuels: Energy security, economics, and the environment. Journal of Agricultural and Environmental Ethics 4, 1–13
[9] Pimentel D (2002): Limits of biomass utilization. Encyclopedia of physical science and technology. New York: Academic Press, pp 159–171
[10] Kim S, Dale BE (2004): Life cycle assessment of various cropping systems utilized for producing ethanol. Biomass and Bioenergy (submitted)
[11] Office of Energy Efficiency and Renewable Energy (2003): Fuel economy guide. DOE/EE-0271. United States Department of Energy/ United States Environmental Protection Agency. Washington DC, USA
[12] United States Environmental Protection Agency (2003): Annual certification test results & data. United States Environmental Protection Agency. Washington DC, USA <http://www.epa.gov/otaq/crttst.htm>
[13] National Risk Management Research Laboratory (2003): Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI): User's Guide and System Documentation. EPA/600/R-02/052. United States Environmental Protection Agency. Ohio, USA

Received: December 7th, 2004
Accepted: February 13th, 2005
OnlineFirst: February 14th, 2005